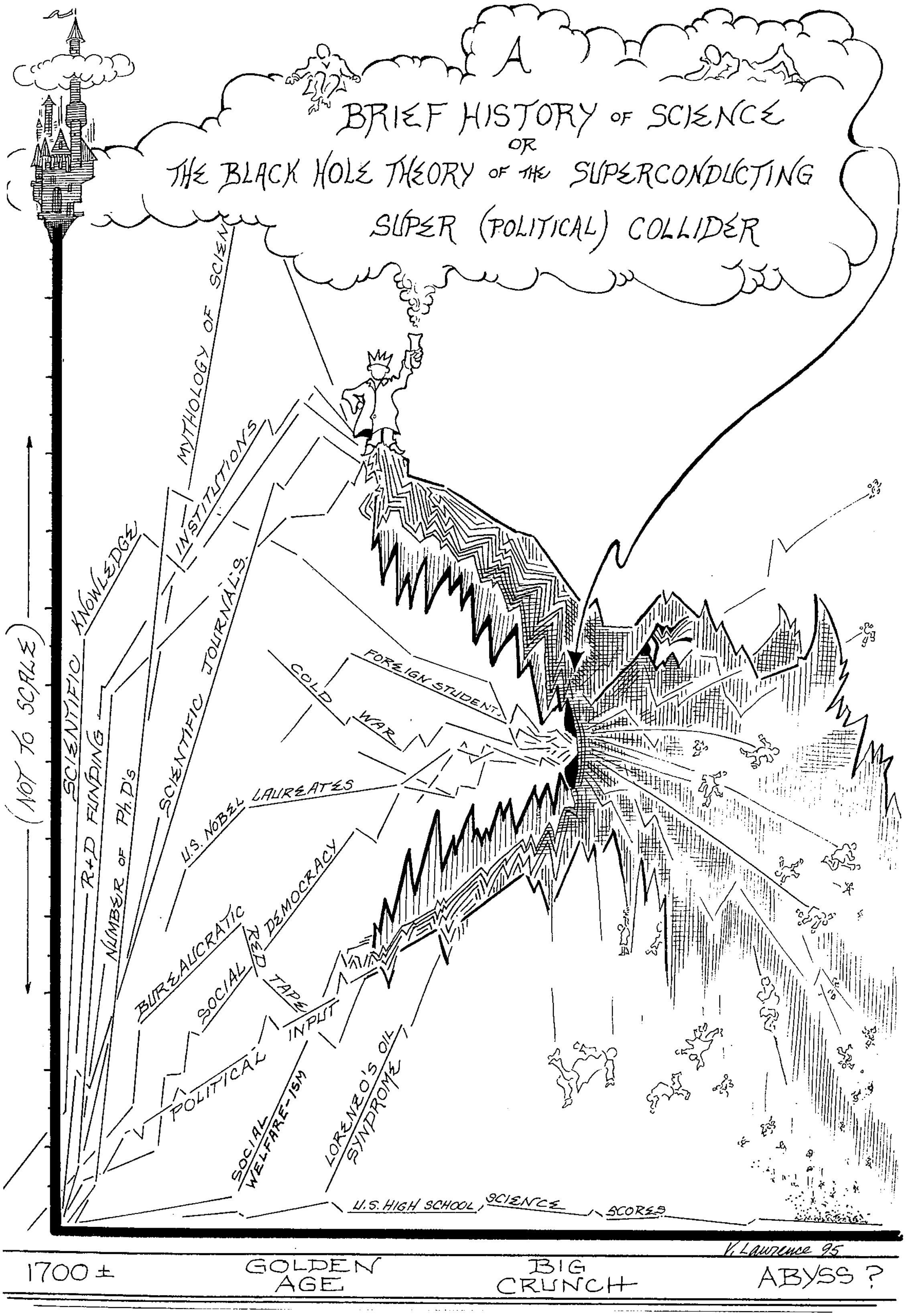
A BRIEF HISTORY OF SCIENCE
OR
THE BLACK HOLE THEORY OF THE SUPERCONDUCTING
SUPER (POLITICAL) COLLIDER
(NOT TO SCALE)
SCIENTIFIC KNOWLEDGE
R+D FUNDING
NUMBER OF Ph.D's
SCIENTIFIC JOURNALS
INSTITUTIONS
MYTHOLOGY OF SCIEN
U.S. NOBEL LAUREATES
COLD WAR
FOREIGN STUDENT
BUREAUCRATIC
SOCIAL
RED TAPE
DEMOCRACY
POLITICAL
INPUT
SOCIAL WELFARE-ISM
LORENZO'S OIL SYNDROME
U.S. HIGH SCHOOL SCIENCE SCORES
V. Lawrence 95
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GOLDEN AGE
BIG CRUNCH
ABYSS ?

The Crisis of Contemporary Science

With the United States no longer engaged in war, hot or cold, American science is entering a new—and uncertain—age. The close relationship between science and government is being redefined. The exponential growth of the scientific enterprise is at an end. And science itself comes increasingly under attack. Our authors explain.

THE CHANGED PARTNERSHIP

BY DANIEL J. KEVLES

Not many years ago in the United States, the special relationship between science and government seemed as permanent as an old-fashioned marriage. Whatever one partner requested, the other was more than eager to provide.

In the early 1980s, for example, American physicists in the field of high-energy particle physics urged the Reagan administration to fund construction of a gargantuan high-energy particle accelerator—the Superconducting Super Collider, commonly called the SSC. In an underground, circular tunnel some 52 miles in circumference, two beams of protons would be accelerated in opposite directions, each to an energy of 20 trillion electron volts. The huge subterranean donut would encircle an area 160 times as great as that enclosed by the Tevatron, at the Fermi National Accelerator Laboratory in Batavia, Illinois, which is the country's flagship machine, spitting out particles at one trillion electron volts.

Enthusiasts of the SSC argued that it was essential to further progress in elementary particle physics. Not only would it guarantee the nation's strength in the field against all international competitors, but the technical innovations required to build the machine—for example, more powerful superconducting magnets—would yield industrial and medical dividends long into the future. In 1987, the project won the support of the Reagan administration, and in 1989, Congress voted decisively to fund construction of the machine—it would be located in Waxahachie, Texas, near Dallas—at a cost of $5.9 billion.

Then, astonishingly, just three years later, the partnership faltered. In June 1992, the House of Representatives voted to terminate the SSC. The margin of defeat for the project was a hefty 51 votes. Scientists who supported the Collider were stunned. Forty physicists, including 21 Nobel laureates, expressed their shock and dismay in a letter to President George Bush and House members, pointing out the SSC's importance to America's scientific prowess. The Bush administration and the Senate then came to the project's rescue. The next year, however, the House tried again, and this time it succeeded. In October 1993, the SSC died, a victim of the post–Cold War outlook. Senator Dave Durenberger (R.-Minn.) explained the change in blunt terms: "If we were engaged in a scientific competition with a global superpower like the former Soviet Union, and if this project would lead to an enhancement of our national security, then I would be willing to continue funding the project. But . . . we face no such threat."

Leading physicists were profoundly dismayed by the collider's demise. They variously declared that high-energy physics had no future in the United States, that the country was relinquishing its role as a scientific leader, and that, as Roy Schwitters, the head of the project, remonstrated, "curiosity-driven science is [now regarded as] somehow frivolous and a luxury we can no longer afford." Some scientists, with a mixture of resentment and regret, declared that the long-standing partnership between American science and the federal government had come to an end.

In fact, it hadn't. But the alliance *is* being redefined. To understand what is happening, it is necessary to go back to the partnership's beginning.

During World War II, civilian scientists working under the auspices of the Office of Scientific Research and Development (OSRD) achieved military miracles. The physicists—who produced microwave radar, proximity fuses, solid-fuel rockets, and the atomic bomb—were the most conspicuous of the scientists, but members of the OSRD Committee on Medical Research also brought off several miracles, including the development of penicillin.

With the war nearing its conclusion, it seemed evident to many policymakers and scientists that for the sake of the nation's military security, public health, and economic welfare, the federal government should support programs of basic and applied scientific research and training in academic institutions, the traditional source of new scientific knowledge and new scientists. The question was how to do so. Two fundamentally different approaches competed for acceptance.

Senator Harley M. Kilgore, a New Deal Democrat from West Virginia and a staunch ally of organized labor, favored what could be called a "social welfare" approach. Kilgore, a small-town lawyer, National Guardsman, Legionnaire, Mason, and past Exalted Ruler of an Elks lodge, was quick to admit "utter, absolute ignorance" of science and technology. However, during wartime hearings on ways of better mobilizing the nation's technological resources, he had learned a good deal about the importance of science to the national interest. Now, looking ahead to postwar America, he began to develop legislation that called for federal research activities to be planned in accordance with liberal social purposes such as aiding small business, fostering pollution control, and providing low-cost rural electrification. Kilgore also wanted at least part of the money in all scientific fields to be distributed geographically. And he urged federal support of the social sciences, then widely regarded as tools for distributing the benefits of science and technology more equitably.

Opposing Kilgore's social welfare notions were Vannevar Bush, head of OSRD, and most of America's high-level research scientists. The Massachusetts-born son of a minis-

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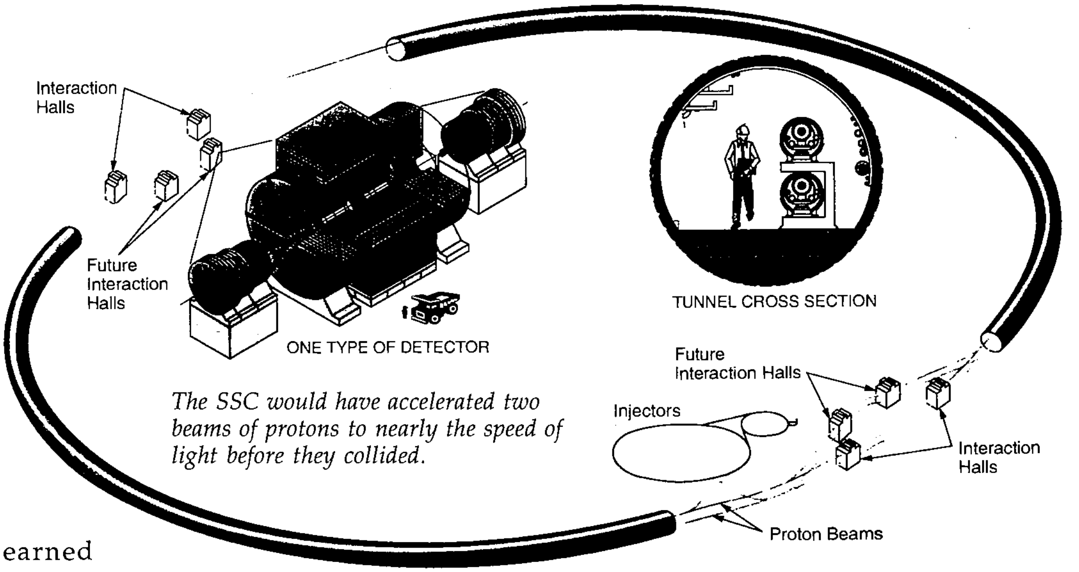
Daniel J. Kevles *is a professor of humanities at the California Institute of Technology. He is the author of* The Physicists: The History of a Scientific Community in Modern America *(1995, 2nd ed.) and* In the Name of Eugenics: Genetics and the Uses of Human Heredity *(1985). Copyright © 1995 by Daniel J. Kevles.*

ter, Bush (1890–1974) was a no-nonsense electrical engineer with a strong sense of public service. He had spent most of his prewar career on the faculty of the Massachusetts Institute of Technology, where the electrical engineering curriculum emphasized training in the basic sciences and the department stressed research. During his MIT years, he earned distinction for his own research, especially for the invention and development of the differential analyzer, an early type of computer. He also played an influential role in transforming MIT into a research-oriented institution at the vanguard of both high-tech engineering and basic science.

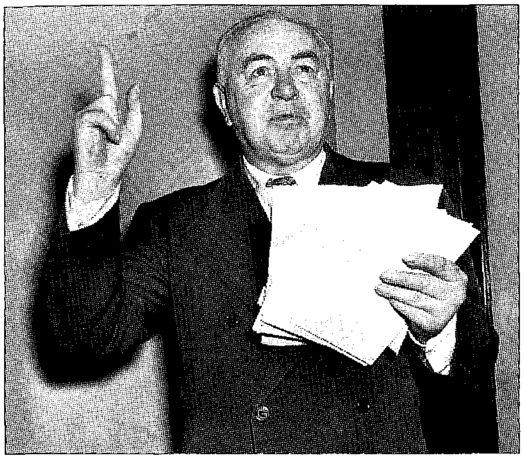


The SSC would have accelerated two beams of protons to nearly the speed of light before they collided.

Bush fully recognized the powerful inclination in America's "practical" culture to foster the applications of knowledge rather than the advancement of knowledge as such. From the war effort, he also knew that advances in esoteric, seemingly impractical fields such as nuclear physics and microbiology could lead to the creation of powerful new weapons and medical agents. In his view, the wartime production of such technological miracles as the atomic bomb and penicillin had drawn heavily on the capital of basic science, and by doing so had retarded the growth of fundamental knowledge and depleted the supply of trained men and women able to generate it. The welfare of the nation demanded the replenishment and enlargement of its scientific investment. But this had to be done in the right way—and that way, he was sure, was not Kilgore's.

Partly to head off the senator, Bush persuaded President Franklin D. Roosevelt to ask him to prepare a report on postwar science policy. Bush delivered the report to President Harry S Truman in July 1945, outlining a policy that, in its essentials, would ultimately prevail.

Bush's approach in *Science—the Endless Frontier*, as the report was called, could not have been more different from Kilgore's. Unlike the senator, Bush gave no consideration to the social sciences, which he regarded as intellectually shoddy, little more, indeed, than political propaganda masquerading as science. His report also made no mention of the geographical distribution of research funds; Bush believed that funding should be distributed among the best investigators, wherever they were located.



Senator Harley Kilgore: a "social welfare" approach

(He maintained, with considerable justification, that most of the significant progress in a scientific field is generated by the most capable practitioners, a relatively small group.) And his report rejected the idea of targeting research to particular social or economic purposes. Above all, Bush held that the social and economic benefits of basic scientific research and training were best realized not by the directives of politicians but by the mechanisms of the free market, by private initiative. Federal science policy, his report stressed, should be insulated from political control.

Bush proposed creation of a "National Science Foundation" to serve as the flagship agency of basic research and training in all the major areas of science, including those related to medicine and the military. He staunchly opposed military domination of science in peacetime, in part because he believed that military influence in American life ought to be limited, but also because he thought that civilian scientists who were independent of military control (as they had been under OSRD) were better able to produce worthwhile innovations, even for military purposes.

Released to the public on July 19, 1945, Bush's report became, as an OSRD staff member remarked, "an instant smash hit," applauded in scores of editorials across the ideological, partisan, and geographical spectrum. *Science—the Endless Frontier* became the charter for a science-government partnership that was to last for almost a half-century.

Still, not everything went according to Bush's plan. By the time the National Science Foundation (NSF) was established in 1950, it had already been pre-empted in the medical area by the National Institutes of Health (NIH), which had been set up in 1948 as an "umbrella" to cover the National Cancer Institute and the new National Heart Institute, and which now comprised five more research institutes, for a total of seven. In the military area, too, the National Science Foundation was vastly overshadowed.

In his postwar science blueprint, Bush had not anticipated that the peace that followed World War II would soon turn into the Cold War with the Soviet Union and communism. But he soon found that the imperatives of that struggle would make national security the predominant focus of federal policy for scientific research and development (R&D). Contrary to his plan, some 90 percent of federal R&D funding would come not from the National Science Foundation but from the armed services, which were consolidated in the Department of Defense in 1947, and from the Atomic Energy Commission, which Congress established in 1946. (Although a civilian agency, the commission devoted its research efforts overwhelmingly to the military uses of atomic energy, especially the development of nuclear, and then thermonuclear, weapons.)

With the outbreak of the Korean War in 1950, the defense R&D budget more than quadrupled, to $3.1 billion in fiscal 1953. Some of it was spent on "basic" research, which, while seemingly impractical, might unexpectedly pay enormous practical dividends (as research into the atomic nucleus had, in the form of the atomic bomb). Another portion went to basic defense research, that is, research into phenomena closely related to military technologies. A larger amount of the money was devoted to "applied" research, intended to produce a specific technology (such as an airplane). And the lion's share of the R&D funds went for "development"—

turning a technological prototype into a finished piece of hardware.

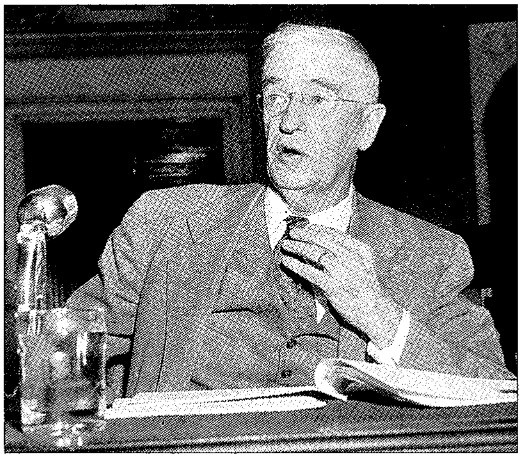
The terminology was loose; one sort of research could easily shade into another. But whatever the labels, a lot more R&D was undertaken. By 1957, the demands of high-tech national security—nuclear warheads, rockets and missiles, antisubmarine warfare and continental defense systems, and scientific manpower—had increased federal R&D expenditures another 10 percent in constant dollars. High-tech industrial research increasingly became a ward of national security, with defense projects supplying an ever-larger fraction—the portion crossed the 50 percent mark in 1956—of total expenditures for industrial research.

The military gave lavish sums to large research universities, supplying them with roughly one-third of all their federal R&D funds. Most of the rest came from the Atomic Energy Commission and, to lesser extents, from the National Science Foundation, NIH, and the Department of Agriculture. A sizable fraction of the military support went to basic research, which, to quote a later Defense Department directive, was recognized "as an integral part of programmed research committed to specific military aims."

Typical of such activity was the Research Laboratory in Electronics at MIT, created to extend the basic microwave research that had been conducted there during the war. Supported by the three armed services, the work was intended to accelerate the transfer of advanced atomic, molecular, solid-state, and microwave physics to engineering practice. The military also became the principal supporter of basic scientific research as such, particularly via the Office of Naval Research (ONR), which before the NSF was established had moved quickly to support the work of astronomers, chemists, physiologists, botanists, logicians, psychologists, computer scientists, and nuclear physicists, among others.

Washington's nondefense R&D budget for science and technology rose with the tide, reaching $16 million in 1956. The NSF supplied a small but significant supplement to the enormous patronage that the Defense Department and the Atomic Energy Commission gave to the nation's universities for research and graduate training in physics, electronics, aeronautics, computers, and myriad other branches of the physical and biological sciences and engineering. In 1955, the NIH budget totaled $81 million and was climbing. Part of the money went to NIH laboratories in the Washington, D.C., area, but at least one-third of it was devoted to research fellowships for promising young biomedical scientists and for basic and applied biomedical research conducted in universities and medical schools.

As much as the federal government was spending on science and technology—$3.9 billion in fiscal 1957, or some five percent of the federal budget—widespread fears soon developed that it was not enough. On October 5, 1957, Americans were shocked to learn that the Soviet Union had launched the world's first artificial Earth satellite, a 184-pound capsule called *Sputnik I*. Then, 29 days later, *Sputnik II*, weighing more than 1,120 pounds, was sent aloft, packed with a maze of scientific instruments and a live dog. The two Sputniks revealed that the Soviets possessed impressive rocket, guidance, and life-support capabilities. After December 6, when



Vannevar Bush: a no-nonsense federal science policy the U.S. attempt to launch a satellite from Cape Canaveral fizzled in a cloud of brownish-black smoke, American alarm at the Soviet achievements increased. Much hand-wringing and self-flagellation ensued. The American character was said to be materialistic and flabby, and America was said to be lagging behind the Soviet Union in science and technology. "Ten years from now the best scientists in the world will be found in Russia," the physicist Edward Teller warned.

The Eisenhower administration promptly established a new White House post of special assistant to the president for science and technology, and MIT president James R. Killian, Jr., was named to fill it. The federal government undertook crash programs to improve high school science facilities and to assist college students in critical scientific fields. In 1958, the National Aeronautics and Space Administration (NASA) was established to oversee the nation's nonmilitary activities in space research and development. "How much money would you need to . . . make us even with Russia . . . and probably leap-frog them?" Representative James G. Fulton (R.-Penn.), asked NASA chief T. Keith Glennan. "I want to be firstest with the mostest in space, and I just don't want to wait for years."

That goal was not achieved overnight, but it didn't take long for federal R&D expenditures to skyrocket. Between 1957 and 1967 they quadrupled, to some $16.5 billion a year—about 11 percent of the federal budget—including more than $2 billion for basic research. In part because of the high priority given to the space program and to biomedical research (the NIH budget reached $400 million in 1960 and $1.4 billion in 1967), the defense-related share of total federal R&D fell from three-fourths to a bit less than one-half.

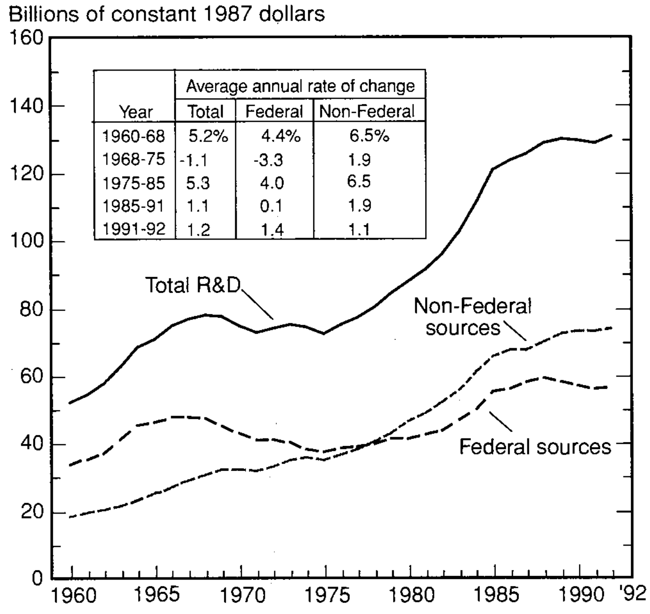
The Cold War competition kept the federal dollars flowing for scientific projects that were deemed significant. In 1958, an advisory panel of physicists pointed out that the Soviet Union proposed to build a 50-billion-volt synchrotron, a machine that would speed up protons to an energy twice that of the most powerful proton accelerator in the U.S. budget. At the time, a proposal from Stanford University was pending at the Atomic Energy Commission for a 10-billion-volt linear accelerator that would send electrons down a two-mile tunnel through the hills near Palo Alto; it would cost $100 million and be the most powerful electron accelerator in the world. In May 1959, President Eisenhower announced that he would ask Congress for the money, declaring that progress in this field was vitally important to the nation.

It was not the intellectual content of the field that was so critical. The more energetic the physical processes that were investigated, the less they had to do with the world of nuclear or thermonuclear processes. As the physicist Robert Wilson said when he testified in favor of constructing the original Fermilab accelerator in the mid-1960s, particle accelerators have nothing to do *directly* with national defense. But the technologies involved in building and operating accelerators—such as high-speed electronics and data analysis—paid real-world dividends. Most important, in terms of the Cold War, the pursuit of high-energy physics provided national prestige and an insurance policy: if something important to national security unexpectedly emerged from the work, the United States would have that knowledge ahead of the Soviet Union.

For academic scientists, the quarter-century after World War II was a golden era. Not only was federal money freely available, but their own professional judgment was given great weight in determining how it was spent. The partnership between science and government might have been dominated by the concerns and agencies of national security, with the NSF given only a minor role to play, but the system still worked pretty much as Bush had proposed. The Department of Defense paid attention to what leading academic scientists and engineers said was worth studying, and grants and contracts went to the scientists and engineers, and the colleges and universities, that were adjudged most capable—regardless of the resulting geographical and institutional concentration of federal dollars. Without overt political control, the system produced basic scientific and technological knowledge, as well as trained technical manpower.

The system proved highly fruitful, to say the least. It yielded not only nuclear weapons and intercontinental missiles but jet planes, computers, silicon chips, nuclear reactors, and Earth satellites for communications and surveillance; chemotherapies for cancer and other medical marvels; advances in molecular genetics, particle physics, and planetary science; and the landing of men on the moon, not to mention myriad consumer items and, indirectly, millions of jobs. American scientists in this golden age received more than three dozen Nobel Prizes, and the United States became the world's leading scientific and technological nation, a mighty and dominant producer of scientific knowledge and high-tech goods.

National R&D Funding



Year	Average annual rate of change		
	Total	Federal	Non-Federal
1960-68	5.2%	4.4%	6.5%
1968-75	-1.1	-3.3	1.9
1975-85	5.3	4.0	6.5
1985-91	1.1	0.1	1.9
1991-92	1.2	1.4	1.1

Source: National Science Foundation, *National Patterns of R&D Resources: 1992*

Since 1985, growth in the nation's total (inflation-adjusted) expenditures on R&D has been slow, with federal funding declining in the early '90s.

Yet for all that, the system was, in truth, not as free of "politics" as it seemed. The decision to make national security the paramount consideration in research policy, the decision to allow scientists and engineers wide latitude in their choice of research programs, and the decision to leave it up to the free market to determine what to do with the resulting social and economic benefits—all these were, in reality, *political* decisions and, as such, subject to change.

In 1965, Harvard University political scientist Don K. Price, a respected analyst of science policy, remarked that Senator Kilgore's "central notions are slipping up on us again."

As the nation became more concerned with poverty, racial inequality, and urban decay, left-of-center critics turned a skeptical eye on federally supported science, particularly its unresponsiveness to social problems and its insulation from political scrutiny and control. As U.S. involvement in the Vietnam War escalated, the criticism turned into searing attacks on universities for allowing the Defense Department to play so large a role in academic research and training, and on science and scientists for their close relationship with the military.

The left-of-center critics had allies among fiscal conservatives distressed by the federal scientific enterprise's increasing absorption of tax dollars. While the federal budget had grown elevenfold since 1940, the R&D budget had exploded some two-hundredfold, a relative growth rate that was bound to draw the attention of budget hawks sooner or later. By the late 1960s, a coalition of liberal and conservative critics had succeeded in bringing the geometric growth of federal spending for science to a halt. On college campuses and in the halls of Congress, the pressure grew to limit the military's role in academic research and the scientific establishment's role in public policy, and, above all, to subject the federal scientific system to greater control in the interest of social welfare. Liberals worked to shift R&D funds into areas they considered more socially useful, such as pollution control, and also sought to bring about a more equitable social, institutional, and geographical distribution of R&D dollars.

President Lyndon B. Johnson, who was intent on waging a "war" on poverty as well as the war in Vietnam, kept asking his science advisers what science had done for "grandma." He instructed the managers of federal science to share the wealth and see about applying all the scientific knowledge already accumulated. LBJ's successor, President Richard M. Nixon, also stressed the seemingly practical. He favored technology—the supersonic transport, the fast-breeder reactor, and antiballistic missiles—over science, and considered the "war" on cancer more important than the advancement of fundamental biology.

By the mid-1970s, the federal R&D budget had, in constant dollars, become 20 percent smaller than what it had been in 1967. Moreover, environmental, energy, and health research commanded a larger proportion of the total outlay, while the space program's share had been cut by half and the defense-related proportion had edged down further, to 46 percent. In 1969, Senator Mike Mansfield (D.-Mont.), a former professor of history and political science who was eager to reduce the military's influence in academic life, had slipped a section into the military authorization bill prohibiting the Pentagon from financing any research not directly related to a specific military purpose. Although the Mansfield amendment was dropped from the military authorization bill the next year, the Pentagon took it lastingly to heart.

Despite the inroads made by Kilgore-style social welfare-ism, the U.S. government remained committed to the hard core of Bush's vision—to federal responsibility for basic scientific research and training, to the involvement of academic and industrial scientists in the policy process, and to the awarding of research funds only to the better investigators. Science policymakers and advisers often managed to interpret mandates for "practical" research programs in such a way that basic investigations were funded. For example, war-on-cancer money paid for basic research into the mechanisms that transform healthy cells into malignant ones, and so sustained the work that led J. Michael Bishop and Harold Varmus, at the University of California, San Francisco, to their Nobel Prize–winning discovery of oncogenes.

Nevertheless, the disturbing trends in federal R&D policy during the 1970s set off various alarms. Some defense specialists contended that the reductions in Pentagon spending, including that for R&D, were making the United States militarily vulnerable. Other worried analysts pointed to the increasingly vigorous foreign competition, especially from Japan, that the United States faced in technological markets not only abroad but at home. Corporate and academic leaders claimed that excessive government regulation was choking industrial and academic science, perhaps even threatening freedom of scientific and intellectual inquiry.

By the late '70s, more and more people were arguing that American military and economic security required an enlarged investment in R&D and a revival of scientific autonomy. The latter would be accomplished by loosening the government's controls on research it funded and by increasing the money

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obtained from alternative sources, particularly industry. "Our engineering and scientific base is disappearing," House Armed Services Committee chairman Melvin Price (D.-Ill.) warned. In the view of many experts, *Business Week* reported, "the future health of the nation's economy . . . requires a much more benign environment for industrial R&D than has existed over the past decade."

As a result of the growing concerns, federal research expenditures grew during the Carter administration and further increased under President Reagan. By the time work began on the Superconducting Super Collider, federal R&D expenditures (in constant dollars) were 20 percent higher than they had been at the predownturn peak, in 1967. The largest share of the increase went to the Department of Defense, whose research programs included semiconductors, optics, lasers, and integrated circuits. These were things that could yield gratifying economic results as well as military ones. Similarly, between 1981 and 1990, the NIH budget (in constant dollars) rose about 50 percent, two-thirds more than the increase in total federal outlays. And at the end of the 1980s, the government established the Human Genome Project, which was estimated to cost $3 billion over 15 years. Designed to map and sequence all the genes in the human genome, the project would not only accelerate biomedical research but enlarge the nation's capacity in biotechnology.

Policymakers and biotechnologists considered biomedical research an important means of strengthening the nation's high-tech competitiveness. The emerging biotechnology industry was founded on basic research that the NIH had supported, particularly the invention of the technique of recombinant DNA during the 1970s by Herbert Boyer and Stanley Cohen, of the University of California, San Francisco, and Stanford University, respectively. With recombinant DNA, a gene from one organism—say, a human being—could be snipped from its native genome and inserted into that of another organism—for example, a bacterium or a mouse—where the function of the gene could be studied, or a valuable protein could be produced. Stanford and the University of California jointly obtained a patent on the technique, which they licensed to biotechnology companies. Among the first to make use of it was Genentech, which enjoyed a spectacular success on the stock market when it went public in 1980.

University patenting of the products of basic research and their licensing into the marketplace appeared to be advantageous to academic institutions, new high-tech businesses, and America's economic competitiveness. In academia, however, there was widespread apprehension that professorial involvements with commercial firms would lead to unsavory exploitation of university resources and students, and might drive out research that had no market promise. Despite all the worries, the incentives pulling academic biologists and their universities toward commercialization—big hits such as Genentech—were too strong to resist.

In the interest of generalizing the policies and practices that fostered the biotechnology industry, the federal government moved to encourage closer collaboration between industry and researchers. In 1980, Congress passed legislation to promote commercial use of inventions arising from federally sponsored R&D at nonprofit institutions. The new patent law made uniform across all government agencies what had been the practice in some, including NIH—namely, to grant property rights in such inventions to institutions that would seek patents on them and license the rights in the market economy. Six years later, Congress passed a law to encourage the commercial use of technologies devised in federal laboratories by, among other things, authorizing government agencies or their employees to license patents on such technologies to private industry.

Industry responded to the incentives for academic collaboration, which were strengthened by university promises of often exclusive patent-licensing arrangements with corporations that supported campus research. Between 1977 and 1986, industry patronage of academic research grew more than fourfold, increasing its share of expenditures for university R&D from around three percent to almost six percent.

In some respects, the shift in R&D policy during the 1980s represented a revival of the fuller vision advanced in *Science—the Endless Frontier*. Vannevar Bush would have been pleased by the resumption of vigorous support for basic research, the marked retreat from the socially purposeful R&D of the 1970s, and the renewed reliance on market mechanisms as the primary means of translating scientific progress into public benefits. Federal R&D funds continued to be allocated mainly to the better-qualified investigators and institutions rather than according to any principle of equity in geographical or institutional distribution. And while the Pentagon's involvement in basic research had increased considerably, in the late 1980s the military supplied only about half the proportion that it did in the mid-1950s and about the same that it did in 1967.

Yet federal science policy—starting in the 1960s with the reappearance of the Kilgore approach of social welfare-ism—had also departed from Bush's vision in important respects. It had become overtly politicized, not in the sense that what might be thought or published was subject to political test, but in the sense that—beginning with the Nixon administration—the views of candidates for appointive advisory and administrative posts on such controversial issues as antiballistic missile policy, the Vietnam War, and the Strategic Defense Inititative were taken into account. The Reagan administration applied tests of political allegiance to candidates for appointment to scientific advisory panels, especially in the regulatory agencies. In the early years of the administration of President Bush, similar tests on issues such as abortion reportedly played a role in appointments to the National Institutes of Health.

Science policy had also become politicized in a more profound sense: the allocation of resources for R&D had been incorporated into the open, conventional political process and become subject to the play of competing interest groups, especially in Congress. Before the late 1960s, the president and the federal bureaucracy had held the upper hand in most areas of science and technology policymaking. They controlled the making of the budget, and they could marshal enormous technical expertise to back up their policy choices.

But they lost that monopoly of power when Congress became more assertive and acquired its own arsenal of expertise on science and technology (beyond the special subject of atomic energy). Legislators hired capable staff members who were knowledgeable in such areas as space, the environment, health, and defense, and over time, individual lawmakers developed their own expertise in particular subjects. Senators and House members also could turn to the Congressional Budget Office for budgetary analyses and to the Office of Technology Assessment for reports on topics ranging from biotechnology to the effects of nuclear war.

As the power to set science policy has become diffused, more and more interest groups, such as environmentalists, feminists, and AIDS activists, have become involved. For federal R&D, that has meant reduced attention to science for its own sake and more to science for social purposes, technological innovation, regional development, and regulation. Thanks to the enactment of laws to strengthen environmental protection, occupational health and safety, public health and medicine, and consumer protection, scientific research has become more integral than ever to regulatory policymaking. Congress also has been challenging the concentrated distribution of federal R&D funds, responding sympathetically to moves by have-not or have-less institutions to circumvent the peer review process by legislating direct grants for the development of laboratory facilities to particular universities.

While scientists continue to enjoy intellectual freedom, the new, open politicization of science policy has meant that the previously most powerful branches of the scientific community—high-energy physics, for example—can no longer decisively determine which inquiries federal monies will stress.

The Superconducting Super Collider was largely done in by the shift to a greater sharing of power between the executive and the legislature in the making of science policy. Made vulnerable by the end of the Cold War, the SSC was forced to stand or fall on its domestic political muscle. On that basis, its strength did not compare with the space station's, which, with a price tag more than twice that of the collider, had commitments of some $8 billion in foreign financing, the heavyweight support of the aerospace industry, and the reported creation of 75,000 jobs to its credit. The vast majority of SSC procurement contracts had gone to only five states, including Texas, where some four times as much money was spent as in second-ranked California. Representative Sherwood Boehlert (R.-N.Y.), an unrelenting enemy of the collider, summarized with only slight exaggeration the political dynamic: "My colleagues will notice that the proponents of the SSC are from Texas, Texas, Texas, Texas, and Louisiana, and maybe someone from California. But my colleagues will also notice that the opponents are . . . from all across the country."

The death of the SSC signified not the end of the partnership between science and government but rather a redirection of its aims and a revision of its operating rules. Now, Senator Kilgore's social welfare approach, as much as Vannevar Bush's vision, is reflected in the partnership's purpose: the advancement of knowledge not only for its own sake but for the sake of specific socioeconomic purposes ranging from industrial competitiveness to environmental management to the battle against particular diseases. And the revised rules of operation make science subject to "normal" political constraints, not the least of them being the pressure to curb federal spending.

In the years ahead, private patrons—both industrial and philanthropic—may well come to shoulder more of the cost of scientific research and training, as they did before World War II. The Howard Hughes Medical Institute, for example, currently supports roughly 10 percent of the basic biomedical research in the United States.

Still, the federal government remains the country's most generous single patron of science, providing in fiscal 1995 roughly $70 billion for R&D, including 60 percent of all monies spent on academic research. If such largesse is spent wisely—that is, if a reasonable portion is devoted to basic research by the most capable scientists—the quality and vitality of American science will not necessarily suffer. But the more it is recognized that the era of sustained exponential growth in science is over, the more difficult it may become for wisdom to prevail. In the SSC controversy, physicists outside the field of high-energy particle physics became involved and helped to kill the project. As the competition for federal research dollars becomes more intense, scientists in all fields, as well as their host institutions, are likely to get involved in political battles in the same way.

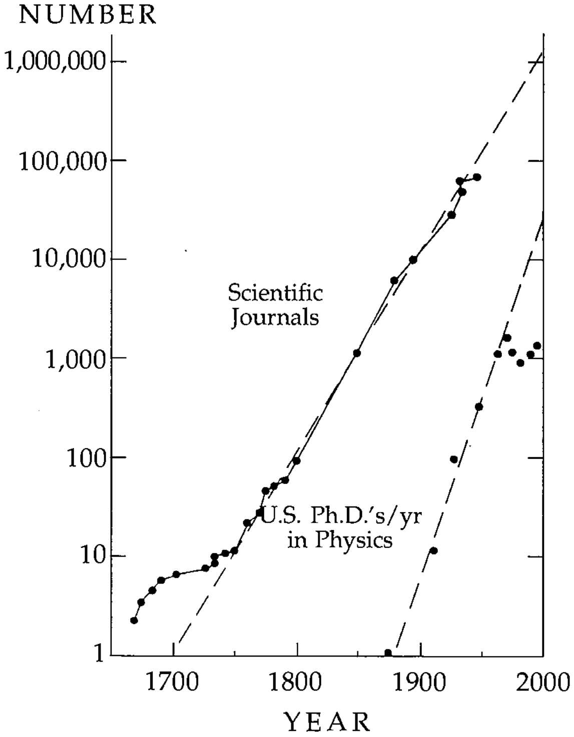
With the end of the Cold War, American science is no longer sacrosanct. Science is in the open political arena and scientists can no longer remain above the fray. Instead, they will have to fight for federal tax dollars, like any other interest group. For them, and for science, it is a new era.

AFTER THE BIG CRUNCH

BY DAVID L. GOODSTEIN

In the beginning, roughly 10 billion years ago according to modern cosmology, was the Big Bang. The universe has been expanding ever since. Whether it will keep doing so forever, we do not know. It may be—if the density of matter in the universe is sufficiently great—that gravitational forces eventually will cause the universe to stop expanding and then to start falling back in upon itself. If that occurs, the universe will end in a cataclysmic event that cosmologists call the Big Crunch.

The history of modern science is somewhat analogous. This science appeared on the scene almost three centuries ago in Europe and slightly more than a century ago in the United States. In each case, it proceeded to grow at an astonishing exponential rate. But while the universe conceivably may expand forever, the exponential enlargement of the scientific enterprise is guaranteed to come to an end.



It is not that scientific knowledge must stop growing. On the contrary, if all goes well, it should continue to expand. But the growth of the profession of science, the scientific enterprise, is bound to reach certain limits. I contend that these limits have now been reached. Many of my scientific colleagues persist in the belief that the future will be like the past and are seeking to preserve the "social structure" of science—the institutions and the patterns of education, research, and funding—that they have come to know so well. If I am right, they won't succeed.

The Big Crunch is here (even if it is actually more like a large whimper than a big bang); indeed, in some fields it has already happened. In physics, it occurred about 25 years ago—and we physicists have been doing our best to avoid the implications ever since. We cannot continue to do so. We must address a question that has never even occurred to the cosmologists: what do you do after the Big Crunch?

The situation can be illustrated by a graph. The upper curve—first published in a book called *Science since Babylon* (1961) by the historian Derek de Solla Price—shows, on a semilogarithmic scale, the cumulative number of scientific journals founded worldwide over the last three centuries. A straight line with a positive slope on this kind of graph means pure exponential growth. If something is increasing that way, then the larger it gets, the faster it grows.

Price's curve, he maintained, is a suitable stand-in for any quantitative measure of the size of science. If so, then modern science appears to have sprung into being around 1700 (the Big Bang might have been the publication of Sir Isaac Newton's *Principia* in 1687) and thereafter expanded exponentially, growing tenfold every 50 years.

Price predicted that this behavior could not go on forever—and, of course, he was right. The straight line in the plot extrapolates to one million journals by the millennium. But the number of scientific journals in the world today, as we near the millennium, is a mere 40,000.

That is only one measure of what is happening, but all the others tend to agree. Consider, in particular, the number of scientists around. It has often been said that 90 percent of all the scientists who have ever lived are alive today. That statement has been true for nearly 300 years—but it cannot go on being true for very much longer. Even with the huge increase in world population in this century, only about one-twentieth of all the people who have ever lived are alive today. It is a simple mathematical fact that if scientists keep multiplying faster than people, there will soon be more scientists than there are people. That seems very unlikely to happen.

I have plotted, on the same scale as Price's curve, the number of Ph.D.'s in physics produced each year in the United States. Like all other quantitative measures of science, this one behaves much like Price's curve. The graph shows that science started later in the United States than in Europe. The first Ph.D. in physics was awarded soon after the Civil War, around 1870. By the turn of the century, the number of doctorates in physics awarded was about 10 per year; by 1930 the annual figure was about 100, and by 1970 it was about 1,000. By extrapolation, there should be one million physics Ph.D.'s given out annually by the mid-21st century, and there now should be about 10,000 awarded per year. But this has not happened. Instead, we have the Big Crunch. The Ph.D. growth stopped cold around 1970, and the number awarded each year has fluctuated around 1,000 ever since. In other fields of science, the timing of the Big Crunch may be a bit different, but not the basic phenomenon. It is inevitable, and it has already begun to happen.

Now, that does not mean that American science has ceased expanding since 1970. It has not. In fact, federal funding of scientific research, in inflation-corrected (1987) dollars, doubled from about $30 billion in 1970 to about $60 billion two decades later. And, by no coincidence at all, the number of academic researchers has also doubled, from about 100,000 to about 200,000. But this rate of growth, controlled by the amount of funding available, is too slow to allow research professors to keep replicating themselves at the same rate as in the past.

If American science were in a steady state condition, the average professor in a research university would need to produce only one future research professor for the next generation. Instead, the average professor, in the course of a typical 30-year career, turns out about 15 students with doctorates—and most such people want to be research professors. As the growth of science slowed in recent decades, it did not take long for the smarter students to realize that not everyone with a Ph.D. could become a research professor. As a result, the number of the best American students who went on to graduate school in science started to drop around 1970, and has been decreasing ever since.

***David L. Goodstein** is vice provost, professor of physics and applied physics, and the Frank J. Gilloon Distinguished Teaching and Service Professor at the California Institute of Technology. He is the author of* States of Matter *(1985) and the host and creator of* The Mechanical Universe, *a PBS television series based on his physics lectures at Caltech.*

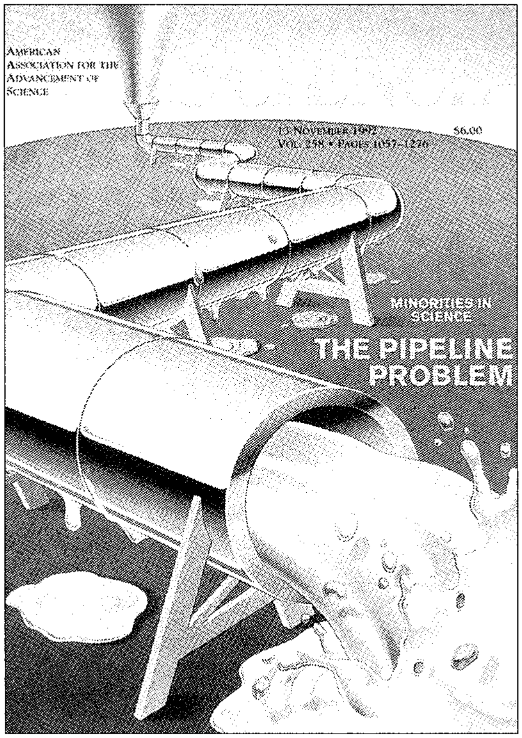
Despite the decline, research professors have been turning out far more scientists than American universities can employ, indeed, far more scientists—now that the Cold War is over and now that the great corporations such as IBM and AT&T have decided to turn away from basic research—than the U.S. government, industry, and academe together can employ.

How have the research professors pulled off this trick? The answer is actually rather simple.

The golden age of American academic science—that is, the 1950s and '60s—produced genuine excellence and made American universities the leaders of the world in scientific training and research. What Europe once was for young scientists in America, America became for young scientists in the rest of the world. They sought to come to the United States, either to obtain an American doctorate or at least to spend a year or more in graduate or postdoctoral study. In short, *foreign* students have taken the places of the missing American students and now constitute roughly half of the Ph.D. holders that American research professors are turning out.

There was one other trick that the professors employed to ward off the effects of the Big Crunch and pretend that it had not occurred. They multiplied the number of postdoctoral research positions, thus creating a kind of holding tank for young scientists that allowed them to put off the unpleasant confrontation with the job market for three to six years, or in some cases even longer.

Since I began with a cosmological analogy, let me now return to one. An unfortunate space traveler, falling into a black hole, is utterly and irretrievably doomed, but that is obvious only to the space traveler. In the perception of an outside observer hovering above the "event horizon," the space traveler's time slows down, so that it seems as if catastrophe can forever be deferred. Something like that has happened in American research universities. The good times ended forever around 1970, but by importing foreign students and employing newly anointed doctors of philosophy as temporary "postdocs," the professors and the universities have stretched time out, allowing them to pretend that nothing important has changed, to think that they need only wait for the good times to return. Only the students realize that they are falling into a black hole.



As this 1992 illustration suggests, leakage in the Ph.D. "pipeline" was widely seen as a major problem.

In spite of all this, only a few years ago, in the early 1990s, many leaders of American science became alarmed that we might not be producing enough scientists and engineers for the future. The problem, they thought, lay with the "pipeline." This metaphor emerged, I believe, from the National Science Foundation, which keeps careful track of science work force statistics, and came to be widely accepted. At the pipeline's entrance was said to be a torrent of youngsters, curious and eager to learn. But as they moved on through the various grades of school, they somehow lost their eagerness and curiosity, and fewer and fewer youths showed any interest in science. The pipeline, in short, was leaking badly, and as a result, there would not be enough Ph.D.'s at the end of the line. The leakage problem was seen as particularly severe with regard to women and minorities. If America is to have all the scientists it will need in the future, we were warned, the leaky pipeline must be fixed. Today, the fear of too few scientists has vanished from the scene, but the pipeline metaphor of science education persists.

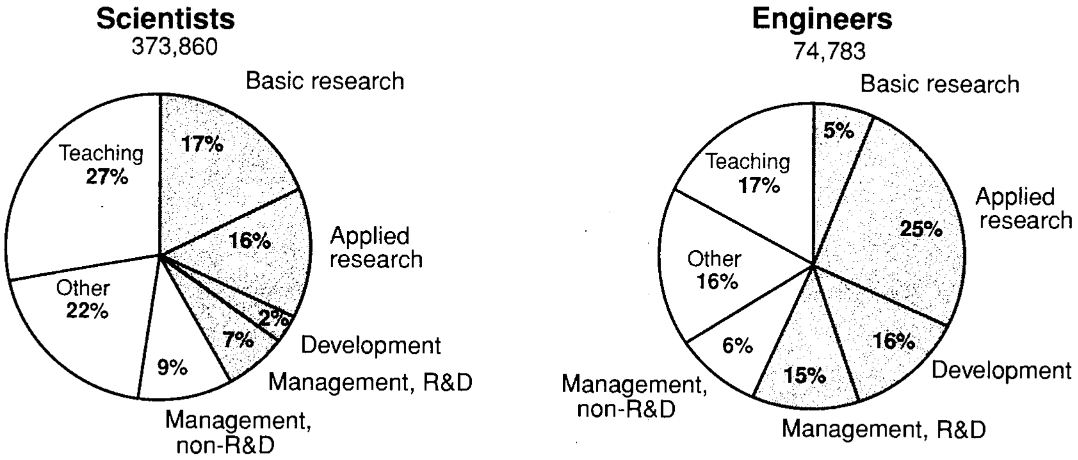
I think the pipeline view of our situation is seriously flawed. The metaphor itself leaks—beyond all repair. The purpose of American education is not to produce holders of doctoral degrees in science or in anything else. The purpose is to create knowledgeable citizens of American democracy who can contribute to their own and the common good. To regard such citizens as somehow deficient because they lack advanced degrees in science is silly, not to mention insulting. Moreover, if American education were a leaky pipeline and could be fixed, the problem that many scientists still do not want to face would remain: what to do with the resulting flood of people with advanced degrees in science.

A more realistic way of looking at American science education, as it is now and has long been, is, I suggest, to view it as a mining-and-sorting operation designed to discover and rescue diamonds in the rough, ones capable of being cleaned and cut and polished into glittering gems, just like us, the existing scientists. Meanwhile, all the other human rocks and stones are indifferently tossed aside in the course of the operation. Thus, science education at all levels is largely a dreary business, a burden to student and teacher alike—until the happy moment arrives when a teacher-miner finds a potential peer, a real, if not yet gleaming, gem. At that point, science education becomes, for the few involved, exhilarating and successful.

This alternative metaphor helps to explain why, in all of the industrialized world, the United States has, simultaneously and paradoxically, both the best scientists and the most scientifically illiterate young people: America's educational system is designed to produce precisely that result. At the same time that American scientists, trained in American graduate schools, win more Nobel Prizes than the scientists of any other country, and, indeed, than the scientists in most, if not all, of the other countries combined, the students in American schools invariably rank at or near the bottom of all students from advanced nations in tests of scientific knowledge. America leads the world in science—and yet 95 percent of the American public is scientifically illiterate.

Let us look a little closer at this mining-and-sorting operation that science education is in America. It begins in elementary school, but only sluggishly and almost without conscious direction. Most elementary school teachers are poorly prepared to present even the simplest lessons in scientific or mathematical subjects. In many colleges, elementary education is the only major that does not require even a single science course. Worse, it is said that many students who choose that major do so precisely to avoid having to take a course in science. To the extent that that is true, elementary school teachers are not merely ignorant of science but determined to remain ignorant. That being so, they can hardly be expected to encourage their students to take an interest in science. Moreover, even those teachers who did have some science courses in college are not likely to be well prepared to teach the subject.

Thus, few elementary school pupils



Primary Employment of Scientists and Engineers

Source: National Science Foundation, *National Patterns of R&D Resources: 1992*

The main work of the 448,600 doctoral scientists and engineers in 1989 (43 percent more than in 1979): for 25 percent, teaching; for 17 percent, applied research; for 15 percent, basic research.

come into contact with anyone who has scientific training, and many decide, long before they have any way of knowing what science is about, that it is beyond their understanding. Nevertheless, some students, a relative handful—usually those who do sense that they have unusual technical or mathematical aptitudes—reach middle school and then high school with their interest in science intact.

There, the mining-and-sorting process gets under way in earnest. Most of the 22,000 high schools in the United States offer at least one course in physics. (Because I have some firsthand knowledge of the teaching of physics in high schools, I shall focus on that, but I am quite sure that what I have to say applies to other science subjects as well.) There are only a few thousand trained and fully qualified high school physics teachers in the United States, far fewer, obviously, than there are high schools. Most of the physics courses are taught by people who in college majored in chemistry, biology, mathematics, or—surprisingly often—home economics (a subject that has fallen out of favor in recent years). These teachers are, in many cases, marvelous human beings who, for the sake of their students, work extraordinarily hard to make themselves better teachers of a subject that had never been their first (or perhaps even their second or third) love. Their greatest satisfaction as physics teachers comes from—guess what?—discovering those "diamonds in the rough" that can be sent on to college for cutting and polishing into real physicists.

That process is not completed in college, of course. Mass higher education, essentially an American invention, has meant that nearly everyone is educated, albeit rather poorly. The contrasting alternative in Europe has been to educate a select few rather well. But in the better U.S. graduate schools, elitism is rescued from the jaws of democracy. In about their second year of graduate school, the students (in physics, at least) finally catch up with their European counterparts and thereafter are second to none.

American education, for all its shortcomings and problems, was remarkably well suited to the era in which the scientific enterprise was expanding exponentially. But after about 1970 and the Big Crunch, the gleaming gems produced at the end of the vast mining-and-sorting operation were

Science for Everyone?

What should an educated person know about science? In The Myth of Scientific Literacy *(Rutgers University Press, 1995), Morris Shamos, a professor emeritus of physics at New York University and a past president of the National Science Teacher Association, contends that trying to make everyone scientifically literate is futile. Instead of offering general students the usual medley of scientific disciplines and asking them to memorize terminology and facts, educators, he says, need to provide students with a broad understanding of what science can—and cannot—accomplish.*

The promise of a *meaningful* public literacy in science is a myth. However good our intentions, we have tricked ourselves into believing that what is being done with science in our schools can lead to such literacy. The folly of this position is that not only do we lack agreement as to the meaning of scientific literacy, but more seriously, we also lack any *proven* means of achieving even the lowest level of science understanding in our educated adult population. . . .

Testifying at a hearing of the Senate Armed Services Committee in November 1957 (soon after Sputnik was launched), the physicist and hydrogen bomb expert Edward Teller likened the need for public support of science to that of the arts. "Good drama," he said, "can develop only in a country where there is a good audience. In a democracy, particularly if the real sovereign, the people, expresses lack of interest in a subject, then that subject cannot flourish." Later in the hearing, giving his views on education in science for the nonscience student, he added: "The mass of our children should be given something which may not be terribly strenuous but should be interesting, stimulating, and amusing. They should be given science appreciation courses just as they are sometimes given music appreciation courses."

Teller's message of science *appreciation*, coming at a time when the American public, and particularly the Congress, was highly sensitive to the issue of Soviet competition in space, and just when massive [National Science Foundation] support for precollege science education was in its formative stage, fell on deaf ears as the nation girded itself for a far more ambitious role in science education, namely, to achieve in the educated public what had never before been accomplished—the intellectual state that came to be known as "scientific literacy."

While not clearly defined at the time (nor even now), this objective carried such a comforting pedagogical feel that one could hardly challenge its premise, and for the next quarter-century the science education community sought to [portray] virtually everything it did as bringing us closer to the goal of scientific literacy. It tried valiantly but it failed badly. . . .

The science and engineering communities, and our nation generally, would be better served by a society that, while perhaps illiterate in science in the formal academic sense, at least is aware of what science is, how it works, and its horizons and limitations. . . .

Teller was perfectly correct in his observation that science must have an appreciative audience, meaning in these times a supportive society, one that values science for its intellectual strength as well as . . . the technologies it spawns. Without such support, science and technology . . . could both flounder, and the United States might indeed become a second-rate nation.

produced less often from American ore. Research professors and their universities, using ore imported from across the oceans, kept the machinery humming.

That can't go on much longer. It is hardly likely that the American public, when it apprehends the situation, will agree to keep pumping vast sums of federal and state money into scientific research in order to further the education and training of foreign scientists. Sooner or later—and in today's post-Cold War environment, it is bound to be sooner—we scientists must face up to the reality of the Big Crunch and learn how to deal with it.

That will not be easy. In 1970, as a young assistant professor of physics at the California Institute of Technology, I circulated a memo among my colleagues pointing out that exponential growth could not be sustained and recommending that Caltech set a dramatic example by admitting fewer graduate students. My faculty colleagues accepted my main argument, but they had a different solution: everyone else should get out of the Ph.D. business, and Caltech should go on just as it was. At every other university where I've broached this subject, I've had precisely the same reaction: not that Caltech should go on as before, but that the particular university I was visiting should.

Harold Brown, who when I circulated my memo was president of Caltech (and who later served as U.S. secretary of defense), had a more creative solution to the problem: make a Ph.D. in physics a prerequisite for any serious profession, just as classical Latin and Greek once had been for the British civil service. (He may have been influenced by the fact that he himself has a Ph.D. in physics but never became a practicing physicist.)

Brown was probably joking. But many scientists today seriously put forth a similar solution. They are advising doctoral candidates on other careers they might pursue after earning the degree that certifies their competence to do scientific research. The little matter of *why* they should become elaborately trained to do something that they are not going to do is seldom brought up.

Why are research professors so eager to produce more future research professors? Of course, most are quite certain that the world will need many more splendid people just like themselves. Their main motive, however, is a little less noble: graduate students are a source of cheap labor. They teach undergraduates, thus freeing the professors to concentrate on research, and they also help the professors do their research. And the graduate students' labor is indeed inexpensive: by their third year, those in science are typically performing difficult, technically demanding work at salaries lower than those received by most starting secretaries.

The arrangement is very convenient for the research professors, but it and the mining-and-sorting operation we call science education in this country cannot go on as they have in the past. The Big Crunch will not allow it. For the new era of constraint, we will have to develop a radically different scientific "social structure," for both research and education. That structure will come about by evolution, not radical redesign, because no one knows what form it will eventually take. One thing, however, is clear: reform of science education must be part of our efforts to adapt the scientific enterprise to the changed conditions.

Pure research in basic science does not reliably yield immediate profit. Hence, if it is to flourish, private support will never be enough. Public funds will continue to be essential. If that support from the public purse is to be forthcoming, there must be a broad political consensus that basic science is a common good. It *is* a common good, for two reasons: first, it helps to satisfy the human need to understand the universe we inhabit, and second, it makes new technologies available. The world would be a very different place without, for example, communications satellites or computers. But to get the public—in the absence of a war, hot or cold—to agree that basic science is worth substantial funding, we scientists are going to have to do a much better job of education than we have in the past. It is no longer enough just to educate a scientific elite.

Really teaching science to people who will never be scientists is not going to be easy. The frontiers of science are far removed from most people's everyday experience. Unfortunately, we scientists so far have not found a good way of bringing people in large numbers along as "tourists" on our scientific explorations.

But that leads me to a modest suggestion: perhaps, after all, there is a reason to keep churning out people with Ph.D.'s in science.

As I indicated before, roughly 20,000 U.S. high schools lack even one fully qualified physics teacher. All of the people with physics Ph.D.'s who are now driving taxis could help to meet that need, and they would be just a beginning.

However, let's be realistic. Before large numbers of people will be willing to obtain a Ph.D. in order to teach in high school, the conditions under which American high school teachers work will have to be substantially improved. I am not speaking here primarily of money. After all, the salaries of beginning schoolteachers today are almost competitive with what postdoctoral fellows receive, and experienced teachers earn salaries comparable to what professors at many colleges get. It would help, of course, if high school teachers were paid better, but that is not the main thing. The real problem is that schoolteachers today are not given the professional respect, freedom, and responsibility that people who have earned Ph.D.'s tend to believe they deserve. I have no blueprint for reform, but I see no intrinsic reason why the prestige of schoolteaching cannot be elevated. In Europe, schoolteachers are highly esteemed precisely because of their superior academic qualifications. Perhaps conditions in the United States now are such that improvement along this line is possible.

Even if education can be reformed, however, that will not be enough. Many of the institutions of science that evolved and worked wonderfully during the long era of exponential growth are gradually breaking down in the new age of constraint. For example, universities have been the real entrepreneurs of science. They raise or borrow funds to put up new laboratory buildings and hire tenured professors to work in them, counting on the professors to bring in grants that will pay off the university's investment. That strategy is becoming suicidal, but many universities seem not to have caught on yet. When they do catch on, or else go belly up, who will build the laboratories of the future? Another example is peer review, long considered a pillar of the system. Anonymous peer review becomes a dangerous game when the author and reviewer are locked in an intense competition for scarce resources. The conflict of interests seems to be obvious to everyone except those who are currently running the system. But what alternative is there to peer review?

We scientists who came of age during the 1950s and '60s must finally recognize that the old era is gone and that, no matter what we do, it is not coming back. We are in a new era now, and it is by no means certain that science as we have known it will even survive. But if we are willing to face the new realities and adapt to them, we may be able not only to rescue the scientific enterprise but to give young Americans something that too many of them now do not have: a basic knowledge of what science has thus far revealed about the world they will inherit. If we can accomplish that, the era of constraint for science may turn out to be a new golden age.

ENEMIES OF PROMISE

BY J. MICHAEL BISHOP

We live in an age of scientific triumph. Science has solved many of nature's puzzles and greatly enlarged human knowledge. And the fruits of scientific inquiry have vastly improved human welfare. Yet despite these proud achievements, science today is increasingly mistrusted and under attack.

Some of the opposition to science comes from familiar sources, including religious zealots who relentlessly press for the mandatory teaching of creationism in the public schools. It is discouraging to think that more than a century after the publication of Charles Darwin's *Origin of Species* (1859), and 70 years after the Scopes trial dramatized the issue, the same battles must still be fought. But fight them we must.

Other antagonists of science are less familiar. Strange though it may seem, there is within academe a school of thought that considers science to be wholly fraudulent as a way of knowing. According to these "postmodernists," the supposedly objective truths of science are in reality all "socially constructed fictions," no more than "useful myths," and science itself is "politics by other means." Anyone with a working knowledge of science, anyone who looks at the natural world with an honest eye, should recognize all of this for what it is: errant nonsense.

Science, of course, is not the exclusive source of knowledge about human existence. Literature, art, philosophy, history, and religion all have their insights to offer into the human condition. To deny that is scientism—the belief that the methods of the natural sciences are the only means of obtaining knowledge. And to the extent that scientists have at times indulged in that belief, they must shoulder some of the blame for the misapprehensions that some people have about science.

But science does have something inimitable to offer humankind: it is, in the words of physician-author Lewis Thomas, "the best way to learn how the world works." A postmodernist poet of my acquaintance complains that it is in the nature of science to break things apart, thereby destroying the "mysterious whole." But we scientists take things apart in order to understand the whole, to solve the mystery—an enterprise that we regard as one of the great, ennobling tasks of humankind.

In the academic medical center where I work, the efficacy and benefits of science are a daily reality. So when I first encountered the postmodernist view of science some years ago, I dismissed it as either a strategy for advancement in parochial precincts of the academy or a display of ignorance. But now I am alarmed because the postmodernist cry has been joined, outside the academy, by other strong voices raised against science.

Consider these lines from Václav Havel, the widely admired Czech writer and statesman, who has vigorously expressed his disenchantment with the ethos of science: "Modern rationalism and modern science . . . now systematically leave [the natural world] behind, deny it, degrade and defame it—and, of course, at the same time, colonize it."

Those are angry words, even if their precise meaning is elusive. And anger is evident, too, in Havel's main conclusion: "This era [of science and rationalism] has reached the end of its potential, the point beyond which the abyss begins."

Even some influential men who know science well and who have been good friends to it in the past have joined in the chorus of criticism and doubt. Thanks in part to Havel's ruminations, Representative George E. Brown, Jr. (D.-Calif.), who was trained as a physicist, reports that his faith in science has been shaken. He complains of what he calls a "knowledge paradox": an expansion of fundamental knowledge accompanied by an increase in social problems. He implies that it shouldn't be that way, that as science progresses, the problems of society should diminish. And he suggests that Congress and the "consumers" of scientific research may have to take more of a hand in determining how science is conducted, in what research gets funded.

A similar critique has been made by former Colorado governor Richard Lamm. He claims no longer to believe that biomedical research contributes to the improvement of human health—a truly astonishing stance. To validate his skepticism, he presents the example of the University of Colorado Medical Center. It has done "little or nothing," he complains, about increasing primary care, expanding medical coverage to the uninsured, dealing with various addictions and dietary excesses, and controlling violence. As if biomedical research, or even academic medical centers, had either the resources or the capabilities to do what Lamm desires!

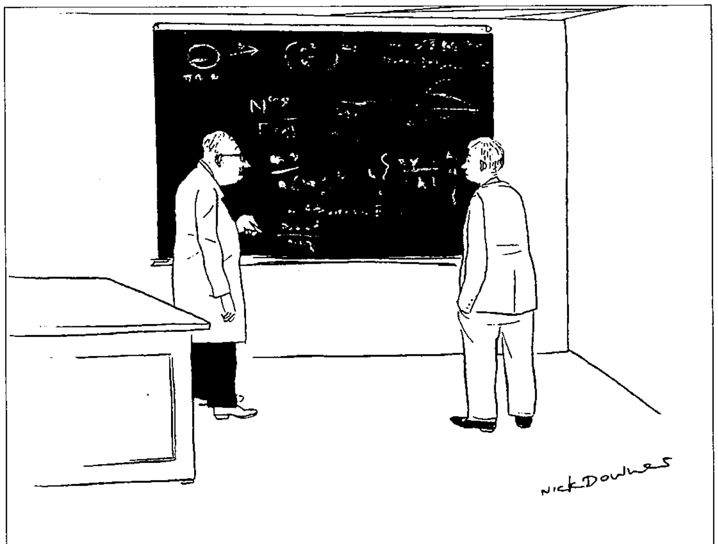
The source of these dissatisfactions appears to be an exaggerated view of what science can do. For example, agitation within Congress may induce the National Science Foundation to establish a center for research on violence, but only the naive would expect a quick fix for that momentous problem. Three-quarters of a century after the death of the great German sociologist Max Weber (1864–1920), the social and behavioral sciences have yet to produce an antidote for even one of the common social pathologies. The genesis of human behavior entails complexities that still lie beyond the grasp of human reason.

Critics such as Brown and Lamm blame science for what are actually the failures of individuals or society to use the knowledge that science has provided. The blame is misplaced. Science has produced the vaccines required to control many childhood infections in the United States, but our nation has failed to deploy properly those vaccines. Science has sounded the alarm about acid rain and its principal origins in automobile emissions, but our society has not found the political will to bridle the internal combustion engine. Science has documented the medical risks of addiction to tobacco, yet our federal government still spends large amounts of money subsidizing the tobacco industry.

These critics also fail to understand that success in science cannot be dictated. The progress of science is ultimately driven by feasibility. Science is the art of the possible, of the soluble, to recall a phrase from the late British immunologist and Nobel laureate Sir Peter Medawar. We seldom can force nature's hand; usually, she must tip it for us.

J. Michael Bishop, is a University Professor of microbiology, immunology, biochemistry, and biophysics at the University of California, San Francisco. He also is director of the G. W. Hooper Research Foundation at the university. He and a colleague, Harold Varmus, were awarded the 1989 Nobel Prize in Physiology or Medicine for their discovery that normal cells contain genes capable of becoming cancer genes.

Nor is it possible, especially in the early stages of research, to anticipate what benefits are likely to result. My own experience is a case in point. In 1911, Peyton Rous at the Rockefeller Institute in New York City discovered a virus that causes cancer in chickens, a seemingly obscure observation. Yet 65 years later, that chicken virus was the vehicle by which Harold Varmus and I, and our colleagues, were able to uncover genes that are involved in the genesis of human cancer. The lesson of history is clear: the lines of inquiry that may prove most fruitful to science are generally unpredictable.



"In layman's terms? I'm afraid I don't know any layman's terms."

Even for educated members of the public, science is largely a mystery.

Biologist John Tyler Bonner has whimsically recalled an exchange he had some decades ago with the National Science Foundation, which had given him a grant for a research project. "After the first year, I wrote that things had not worked out very well—I had tried this, that, and the other thing, and nothing had really happened. [The foundation] wrote back, saying, 'Don't worry about it—that is the way research goes sometimes. Maybe next year you will have better luck.'" Alas, no scientist today would think of writing such a report, and no scientist today could imagine receiving such a reply.

The great successes of science have helped to create the exaggerated expectations about what science can accomplish. Why has malaria not been eradicated by now? Why is there still no cure for AIDS? Why is there not a more effective vaccine for influenza? When will there be a final remedy for the common cold? When will we be able to produce energy without waste? When will alchemy at last convert quartz to gold?

When scientists fail to meet unrealistic expectations, they are condemned by critics who do not recognize the limits of science. Thus, playwright and AIDS activist Larry Kramer bitterly complains that science has yet to produce a remedy for AIDS, placing much of the blame on the National Institutes of Health (NIH)—"a research system that by law demands compromise, rewards mediocrity and actually punishes initiative and originality."

I cannot imagine what law Kramer has in mind, and I cannot agree with his description of what the NIH expects from its sponsored research. I have assisted the NIH with peer review for more than 20 years. Its standards have always been the same: it seeks work of the highest originality and demands rigor as well. I, for one, have never knowingly punished initiative or originality, and I have never seen the agencies of the NIH do so. I realize with sorrow that Mr. Kramer is unlikely to believe me.

Biomedical research is one of the great triumphs of human endeavor. It has unearthed usable knowledge at a remarkable rate. It has brought us international leadership in the battle against disease and the search for understanding. I wonder how all this could have been accomplished if we scientists did business in the way that Kramer and critics like him claim that we do.

The bitter outcry from AIDS activists over the past decade was echoed in the 1992 film *Lorenzo's Oil*, which portrays medical scientists as insensitive, close-minded, and self-serving, and dismisses controlled studies of potential remedies as a waste of precious time. The film is based on a true story, the case of Lorenzo Odone, a child who suffers from a rare hereditary disease that cripples many neurological functions and leads at an agonizing pace to death.

Offered no hope by conventional medical science, Lorenzo's desperate parents scoured the medical literature and turned up a possible remedy: the administration of two natural oils known as erucic and oleic acid. In the face of the skepticism of physicians and research specialists, Lorenzo was given the oils and, in the estimation of his parents, ceased to decline—perhaps even improved marginally. It was a courageous, determined, and even reasoned effort by the parents. (Mr. Odone has since received an honorary degree from at least one university.) Whether it was effective is another matter.

The movie portrays the treatment of Lorenzo as a success, with the heroic parents triumphant over the obstructionism of medical scientists. The film ends with a collage of parents testifying that the oils had been used successfully to treat Lorenzo's disease in their children. But it fails to present any of the parents who have tried the oils with bitter disappointment. And, of course, all of this is only anecdotal information. Properly controlled studies are still in progress. To date, they have not given much cause for hope.

Meanwhile, as if on cue, medical scientists have since succeeded in isolating the damaged gene responsible for the rare disease. Thus, the stage is set for the development of decisive clinical testing and effective therapy (although the latter may be long in coming).

If misapprehensions abound about what science can and cannot do, so do misplaced fears of its hazards. For more than five years now, my employer, the University of California, San Francisco, has waged a costly battle for the right to perform biomedical research in a residential area. For all intents and purposes, the university has lost. The opponents were our neighbors, who argued that we are dangerous beyond tolerance; that we exude toxic wastes, infectious pathogens, and radioactivity; that we put at risk the lives and limbs of all who come within reach—our own lives and limbs included, I suppose, a nuance that seems lost on the opposition. One agitated citizen suggested in a public forum that the manipulation of recombinant DNA at the university had engendered the AIDS virus; another declared on television her outrage that "those people are bringing DNA into my neighborhood."

Resistance to science is born of fear. Fear, in turn, is bred by ignorance. And it is ignorance that is our deepest malady. The late literary critic Lionel Trilling described the difficulty well, in words that are even more apposite now than when he wrote them: "Science in our day lies beyond the intellectual grasp of most [people]. . . . This exclusion . . . from the mode of thought which is habitually said to be the characteristic achievement of the modern age . . . is a wound . . . to our intellectual self-esteem . . . a diminution of national possibility . . . a lessening of the social hope."

The mass ignorance of science confronts us daily. In recent international testing, U.S. high school students finished ninth in physics among the top 12 nations, 11th in chemistry, and dead last in biology. Science is poorly taught in most of our elementary and secondary schools, when it is taught at all. Surveys of adult Americans indicate that only a minority accepts evolution as an explanation for the origin of the human species. Many do not even know that the Earth circles the Sun. In a recent committee hearing, a prominent member of Congress betrayed his ignorance of how the prostate gland differs from the testes. Accountants, laborers, lawyers, poets, politicians, and even many physicians look upon science with bewilderment.

Do even we scientists understand one another? A few years ago, I read of a Russian satellite that gathers solar light to provide constant illumination of large areas of Siberia. "They are taking away the night," I thought. "They are taking away the last moments of mystery. Is nothing sacred?" But then I wondered what physicists must think of biologists' hopes to decipher the entire human genome and perhaps recraft it, ostensibly for the better.

Writing an article about cancer genes for *Scientific American* some years ago, I labored mightily to make the text universally accessible. I consulted students, journalists, laity of every stripe. When these consultants all had approved, I sent the manuscript to a solid-state physicist of considerable merit. A week later, the manuscript came back with this comment: "I have read your paper and shown it around the staff here. No one understands much of it. What exactly is a gene?"

Robert M. Hazen and James Trefil, authors of *The Sciences: An Integrated Approach* (1994), tell of 23 geophysicists who could not distinguish between DNA and RNA, and of a Nobel Prize-winning chemist who had never heard of plate tectonics. I have encountered biologists who thought string theory had something to do with pasta. We may be amused by these examples; we should also be troubled. If science is no longer a common culture, what can we rightfully expect of the laity by way of understanding?

Lionel Trilling knew where the problem lay in his time: "No successful method of instruction has been found . . . which can give a comprehension of science . . . to those students who are not professionally committed to its mastery and especially endowed to achieve it." And there the problem lies today: perplexing to our educators, ignored by all but the most public-minded of scientists, bewildering and vaguely disquieting to the general public.

We scientists can no longer leave the problem to others. Indeed, it has always been ours to solve, and all of society is now paying for our neglect. As physicist and historian of science Gerald Holton has said, modern men and women "who do not know the basic facts that determine their very existence, functioning, and surroundings are living in a dream world . . . are, in a very real sense, not sane. We [scientists] . . . should do what we can, or we shall be pushed out of the common culture. The lab remains our workplace, but it must not become our hiding place."

The enterprise of science embodies a great adventure: the quest for understanding in a universe that the mathematician Freeman Dyson once characterized as "infinite in all directions, not only above us in the large but also below us in the small." We of science have begun the quest well, by building a method of ever-increasing power, a method that can illuminate all that is in the natural world. In consequence, we are admired but also feared, mistrusted, even despised. We offer hope for the future but also moral conflict and ambiguous choice. The price of science seems large, but to reject science is to deny the future.